Reliability-based Design, Development and Sustainment

NDIA’s 2007 T&E Conference:
*T&E in Support of Operational Suitability, Effectiveness and Sustainment of Deployed Systems*

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Briefing Overview

- Description of reliability-based methods
- Applications and results
- Implications of reliability-based methods for T&E
- Challenges
- Path ahead
ARA BUSINESS AREAS

- National Defense
- Transportation
- Security Risk & Disaster Management
- Geotechnical & Environmental Technologies
- Computer Software & Supporting Technologies

Expanding the Realm of Possibility
Introduction

- Reliability-based methods are those that
  - Use the probability of failure as a criterion in the design process
- These methods contribute to suitability, effectiveness and sustainability by
  - Improving system performance
  - Increasing operational readiness
  - Reducing unnecessary intervention or maintenance
  - Managing spare parts inventories
  - Reducing technical and operational risk
- Other benefits of these methods
  - Provide predicted performance across a range of metrics
  - Support decision-makers by highlighting trade-offs in performance and RAM
The “Magic” behind the Methods

- These methods involve
  - Applying probability distributions to uncertainties
  - Using physics-based modeling to assess the impact of these uncertain factors on system performance
  - Balancing system design features and inspection intervals against risk
Physics-based Probabilistic Analysis

**PRObabilistic Function Evaluation System**

- **Model Uncertainties and Variability**
- **Develop High Fidelity Computational Models**
- **Apply State-of-the-Art probabilistic methods**

Focus on “Weakest Links” and Most Likely Causes for Failures

Compute:
- Risk
- Reliability
- Reliability sensitivities
- Response probability distributions
- Failure samples for maintenance simulation

Optimize:
- Risk and Reliability
- Maintenance Plan
- Test Plan

Expanding the Realm of Possibility
Reliability-based Methods that support Suitability, Effectiveness and Sustainability

- Reliability-based multidisciplinary optimization (RBMDO)
- Reliability-based damage tolerance (RBDT)
Reliability-based Multi-disciplinary Optimization (RBMDO)

- Optimizes performance subject to multiple reliability-based constraints
- Incorporates multi-disciplinary objectives/models (e.g., payload, aerodynamics, shape parameters, weight, …)
- Accomplishes higher performance over independent optimization of each discipline
**RBMDO Application – Aircraft Wing Design**

- NASTRAN model of Advanced Composite Technology (ACT) wing
- Baseline aircraft: proposed 190-passenger, two-class, transport aircraft
- Critical Design conditions derived from DC-10-10 and MD-90-30

- 3804 finite element nodes
- 3770 finite elements (2222 shells + 1548 beams)
- 22 material properties
- 47 shell element properties
Performance-based objective and reliability-based constraints

Weight is reduced while reliability is improved
Another Application – Radiation Detector Sustainment

Expanding the Realm of Possibility
Reliability-Based Damage Tolerance (RBDT) Framework

Fully Integrated Finite Element stress, Fracture Mechanics life and ProFES analyses

Principal Structural Element Model
- stress model
- life model

Fracture Mechanics Damage Tolerance
Crack Size
Update distribution after maintenance
Initial Flaw
1st Insp.
2nd Insp.
Time (Flight hours)

Non-Destruct. Inspection Planning
Cum. Probability
0
1
Crack Size
Initial
At Insp.
POD

Material
Usage
Load Spectra
Stress
Flaw or FOD
Modeling Error
Inspection time

Joint probability density
Most Likely Failure Point
Failure Sampling
Failure Samples

ProFES
Max. risk reduction
Without Inspection
With Inspection

Expanding the Realm of Possibility
Reliability-Based Damage Tolerance (RBDT) Methodology for Rotorcraft Structures

- Project sponsored by FAA
- Critical structures must maintain very small probability of failure
- Supplement current “safe-life” design approach (which tends to be too conservative)
- Systematically treat variability/uncertainty in:
  - usage, load, flaw, material, geometry, modeling error, defect detection capability
- Maintenance planning for:
  - Non-Destructive Inspection, inspection frequencies, repair/replacement
- Has wide applicability to structures with material or manufacturing flaws
  - Select appropriate NDI interval
  - Optimize sustainment strategies

<table>
<thead>
<tr>
<th>Underlying Principles</th>
<th>Deterministic</th>
<th>Probabilistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flaw/Defect size</td>
<td>A given crack size</td>
<td>Probabilistic distribution</td>
</tr>
<tr>
<td>Flaw Existence</td>
<td>Certain (Safe-Life)</td>
<td>0 &lt; Probability &lt; 1</td>
</tr>
<tr>
<td>Inspection Schedule</td>
<td>Life/No. of inspections</td>
<td>Optimized schedules for max. risk reduction</td>
</tr>
<tr>
<td>Safety Measure</td>
<td>Safety margin</td>
<td>Reliability</td>
</tr>
<tr>
<td>Other Variables</td>
<td>Bounds or Safety Factors</td>
<td>Distributions</td>
</tr>
</tbody>
</table>

Max. risk reduction

Flight Hours

Prob. of Fracture

Without Inspection

With Inspection
Expanding the Realm of Possibility

RBDT Application -- Rotorcraft Spindle Lug Model

Goal – Optimize inspection schedule to minimize risk

Random variables for the lug model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution</th>
<th>Mean</th>
<th>SD</th>
<th>Cov (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness, $t$ (mm)</td>
<td>LN</td>
<td>28</td>
<td>0.14</td>
<td>0.50</td>
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<tr>
<td>Max. load (N)</td>
<td>LN</td>
<td>145000</td>
<td>10000</td>
<td>6.9</td>
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<tr>
<td>Initial flaw size (mm)</td>
<td>User-defined</td>
<td>0.074</td>
<td>0.0224</td>
<td>30.2</td>
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<tr>
<td>Delta $K_{th}$</td>
<td>LN</td>
<td>48</td>
<td>4</td>
<td>8.33</td>
</tr>
<tr>
<td>Life scatter</td>
<td>LN</td>
<td>1</td>
<td>0.1</td>
<td>10.0</td>
</tr>
</tbody>
</table>

Reference $R = 0.25m$, Thickness = 67 mm, Initial flaw size = 0.4 mm
RBDT Yields Optimal Inspection Schedule

Systematic approach for probabilistic fracture mechanics damage tolerance analysis with maintenance planning under various uncertainties

Stage 1: compute risk without inspection

Stage 2: compute risk with inspection by simulating inspection and maintenance effects using the samples generated from the Stage 1 failure domain

Reducible Risk = \( p_C \cdot p_D \)

= \( [p_f^0(t_{Service}) - p_f^i(t_{Insp})] \cdot E[POD(a_{Crit.parts})] \)
Reliability-based Damage Tolerance Application
Pipeline Maintenance Optimization

- Corrosive environments cause metal losses
- Two major failure modes with uncertainties
  - Burst can cause a high consequence but is less likely to occur
  - Leak has a low consequence but is more likely to occur
- In-line inspection devices can detect significant defects
- Options to maintain integrity at different risk/cost:
  - Defect monitoring using high resolution ILI devices (cost issue)
  - Repair/replace sections (cost issue)
  - Reduce operating pressure (production loss)
  - Corrosion mitigation (cost issue)
- Objective
  - Develop maintenance optimization software using ILI data and probabilistic failure and cost models

In Line Inspection
Magnetic Flux Leakage and other ILI devices can travel through pipelines to detect metal losses
Pipeline Maintenance Example

Pipeline Maintenance Optimization Methodology

Risk is minimized if the next inspection and repair time is 3 years from the last inspection.
Another Application – Robotic/Unmanned Systems Design
Implications for T&E

Material Testing

Material Constitutive Modeling

Component Analyses

Subassembly Analyses

Global Analyses

Observables

Building block approach requires testing at all levels
Wrap-up

Accomplishments
- Tools for taking a reliability-based approach to design and sustainment that can result in cost savings and risk reduction
- Traceable predictions of reliability and performance changes
- Computationally fast and efficient methods

Challenges
- Scalability of approach
- Understanding material failure properties
- Cascade of variable and interrelationships
  - Non-unitized structures
- “User friendliness”
  - Enable use by decision-makers
Path Ahead

- Mature/prove methods for specifying probability distributions
  - ARA’s Klein Associates Division (cognitive scientists)
- Refine the understanding of the impact and interaction of the uncontrollable random variables
- Accelerate collection of data to inform physics-based models
- Continue to evolve cost- and time-effective testing approaches for verifying reliability